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The Role of Fresh Air Nozzle Orientation and Warehouse Dimensions in Modulating Airflow and Temperature in Pharmaceutical Warehouses: A Comparative Study

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ABSTRACT: This study investigates the effects of fresh air inlet angle, warehouse height, and shelf occupancy on airflow and temperature distribution in pharmaceutical warehouses through parametric and multi-objective optimization analyses. A two-dimensional model of the warehouse is developed and analyzed using Computational Fluid Dynamics via ANSYS Fluent software. Results indicate that increasing the warehouse height from 3 to 5 and 7 meters leads to reductions in average temperature by 1.4% and 2.2%, respectively, and temperature variation by approximately 32% and 42.2%. Lower shelf occupancy provides the most favorable thermal conditions, while medium occupancy results in the poorest performance in terms of both average temperature and uniformity. As the air inlet angle increases from vertical, temperature rises and uniformity deteriorates. Horizontally, shelves farther from the symmetry axis exhibit higher temperatures and less uniformity. Vertically, middle shelves show better thermal performance than upper or lower ones. Additionally, increasing the warehouse height reduces average air velocity. Optimization results reveal the best configuration by balancing temperature and its uniformity. These findings provide insights into improving the thermal environment of pharmaceutical storage spaces to preserve drug quality and reduce energy consumption, guiding design improvements for Heating, Ventilation, and Air Conditioning systems in such facilities.

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1- Introduction

Pharmaceutical warehouses have an essential role in the medicine industry. Proper medicine storage in a warehouse requires specific conditions, with the permissible temperature range being one of the most crucial factors. In order to maintain the temperature within an acceptable range, an HVAC system is necessary. The warehouse dimensions, the grilles geometry and the shelves arrangement can affect the air distribution and temperature quantity and uniformity. Computational Fluid Dynamics (CFD) stands out as a highly effective method for analyzing HVAC systems. Numerous studies have focused on simulating airflow within buildings and examining its impact on indoor temperatures. Popovici and Hudisteanu [1]carried out HVAC calculations for a theater in two cases (occupied and break time) using CFD and a two-dimensional Fluent model and compared them. Predictably, the outcomes of these two scenarios were entirely dissimilar; nonetheless, due to the appropriate choice of HVAC system, both cases encountered no issues. Popovici [2]simulated an amphitheater in two dimensions using ANSYS-Fluent software and k-ε as turbulence model. Summer and winter conditions were compared. Maximum speed of the air in summer was more than winter; however, because of the careful selection of the HVAC system, neither case faced any difficulties. Saving energy and maintaining temperature in the allowable range are vital for products storage. Park et al.[3] proposed an algorithm to set inlet air flow and its properties to control the temperature of the warehouse. The comparison of the results with thermostat-based control shows a 6.4% energy saving and a 21.2% reduction in thermal dissatisfaction. Ensuring Thermal comfort of warehouse staff can be a crucial objective for clients. The uniformity of temperature in large environments was another area of research for Shan et al.[4], who specifically studied an open office space in Hong Kong. Their study employed Energy-Plus and ANSYS-Fluent, dividing the extensive space into multiple subzones. Fluent was applied to measure the temperature and air flow rate through the virtual partition walls. The integration of these two software solutions resulted in greater temperature consistency and minimized energy consumption. Khodabande et al. [5] executed a numerical analysis to assess the effects of various air distribution methods on the cooling quality of a data center, using the 6SIGMADCX software package. Their research showed that the addition of partitions in the cool and warm air passages permits an increase in the inlet air temperature beyond the acceptable limit, leading to lower energy losses and greater efficiency. They suggested

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implementing return air channeling and access floor partitioning as additional strategies. The research [6]focused on the impact of inlet grille arrangements on both indoor air quality and energy consumption, with thermal comfort as a key consideration in an amphitheater environment. They explored four different strip shapes for the grilles through simulation and offered various recommendations to improve indoor air quality and thermal comfort. Among these, the installation of inlet air grilles in the floor was highlighted, leading to a 20% enhancement in efficiency and a 10% decrease in pollutant levels relative to alternative designs. Angeles-Rodríguez and Celis [7]examined the impact of the location of inlet and outlet air grilles on the efficiency of HVAC systems within a room. They simulated 20 various configurations using ANSYS-Fluent, calculating both temperature and air velocity. The research concluded by identifying the optimal grille positions based on three key factors: efficiency, average temperature, and the vertical gradient of temperature. Wang and Li [8]conducted a study on air stratification because of temperature gradients and variations in density within large warehouses. Their research employed CFD simulations alongside local measurements, with an emphasis on quantifying thermal stratification. They implemented appropriate modeling techniques for air mixing devices, including ceiling-mounted rotating fans and bucket fans. In their research, Pichurov et al. [9]analyzed HVAC control systems through airflow studies using CFD. They compared two scenarios with different air inlet configurations, demonstrating the utility of CFD in this field. The analysis presented by Kim et al. [10]focused on heating and cooling loads, employing a coupled simulation that encompasses convection, radiation, and HVAC control systems. This research considered the actual output feedback from the HVAC system as boundary conditions of CFD. A comparison was made between two distinct HVAC systems, and the clothing conditions of the occupants were assessed. The findings indicated that the radiation-panel cooling system outperformed the all-air cooling system in semi-enclosed spaces. The study by Garnier et al. [11]investigated the application of predictive control in HVAC systems for nonresidential buildings, employing EnergyPlus software to assess an existing facility. Through the use of a genetic algorithm for optimization, they were able to determine the ideal timings for the activation and deactivation of HVAC subsystems. The findings indicated that the implementation of predictive control significantly lowered energy consumption while simultaneously enhancing thermal comfort. Naboni et al. [12]introduced a thermal comfort strategy for architectural design through the application of CFD. The crucial role of preparing and relocating partitions at different times was highlighted as essential for enhancing HVAC systems and saving energy. The investigation by Heidari Nezhad et al. [13]focused on the relationship between the height of return air grilles and its effects on energy consumption, thermal comfort, and air quality in under-floor air distribution systems. By employing Air Pak software with the SIMPLE algorithm for CFD, the researchers established the optimal height for the return air grille, achieving a 15% energy savings without compromising thermal comfort or indoor air quality. The research conducted by Imani Nezhad et al. [14]focused on how the positioning of fresh air grilles impacts indoor air quality and the thermal comfort for residents in a winter condition within a room featuring cornice-shaped heaters. Their findings indicated that modifying the grilles' location influenced the average temperature by more than 1 degree Celsius and improved indoor air quality from a measurement of 0.44 to 0.67. An analysis was carried out by Amin Zade et al.[15] to examine the influence of return air grille positioning in an industrial environment that utilizes high-temperature radiators, focusing on the uniformity of thermal conditions and the emission of pollutants. Their findings indicate that placing the return air grille close to the ceiling significantly lowers carbon dioxide levels. Kanaan [16]conducted an optimization study focusing on the balance between return air ratio and ultraviolet light for disinfection within an integrated air conditioning and heat recovery system, utilizing CFD techniques. His research aimed to improve the return air ratio while ensuring that indoor air quality remained acceptable. He successfully conducted simulations of CO_2 diffusion and aerobic bacteria with CFD and subsequently made arrangements for sterilization. Almansa et al. [17]introduced a methodology for simulating a conventional diffuser through the integration CFD and empirical data. This approach involved a reduction in the number of points utilized to analyze airflow within the room. At high Reynolds numbers, a comparison was made between the experimental data and the outcomes of the numerical analysis. The findings indicated that the pressure drop derived from the simulation aligned closely with the experimental measurement. The research by Ho et al.[18] involved simulating a refrigerated warehouse to analyze temperature and airflow characteristics. They discovered that increasing the velocity of the inlet air and locating the cooling units nearer to the product packages significantly enhanced efficiency and promoted a more uniform temperature throughout the space. In her research, Talbot [19]engineered a refrigeration system intended for food storage, where she sought to establish an efficient refrigeration cycle and determine the most suitable refrigerant and temperature ranges to maximize the system's efficacy. Her analysis included a cost assessment for the compressor, condenser, and evaporator, utilizing thermodynamic principles.

Concilio et al.[20] examined the air quality within a classroom-laboratory in Madrid, Spain, where no ventilation was supplied. The considerable height of the room promoted air stratification, which was assessed through the analysis of temperature and CO_2 distribution. A numerical model utilizing CFD was established to investigate the air quality. The flow dynamics were derived by solving the complete three-dimensional Navier-Stokes equations, coupled with thermal analysis. The research considered three scenarios: occupants in seated positions, standing positions, and a combination of both.

There are more studies related to this paper's subject:

Bishnoi and Aharwal[21] examined temperature non-uniformity within fruit storage facilities. Elias et al. [22] presented a simulation for evaluating the performance of a fuzzy logic controller designed for temperature and humidity regulation in pharmaceutical warehouses, utilizing the MATLAB Fuzzy Logic Toolbox and MATLAB Simulink. Tabašević et al. [23]conducted temperature mapping in pharmaceutical storage areas and optimized the location of temperature sensors for improved control. Pachano et al.[24] focused on optimizing the parameters and performance characteristics of various cooling system components through the use of jEPlus software. Zhang et al. [25] developed a semi-coupled CFD model to analyze the flow and temperature distribution within refrigerated spaces. Brunetti[26]explored optimal strategies for constructing a passively-cooled pharmaceutical warehouse in regions characterized by hot and humid climates. Shao and Riffat [27]investigated the precise calculation of pressure losses in HVAC duct fittings and other significant factors. Yamamoto et al. [28]studied the integration of radiant panels with air conditioning systems to achieve optimal thermal control in residential settings, employing CFD and energy simulation techniques. Ascione et al. [29] reported energy savings resulting from enhancements to the thermal and physical properties of the building envelope, with reference to a medium-sized hospital situated in a Mediterranean climate.Various factors can affect the temperature and its uniformity within a pharmaceutical warehouse. As well as inlet/outlet grilles arrangement, the angle of inlet air flow may be influential, especially when shelves are occupied by medicine packages that disrupt airflow patterns. It is necessary to evaluate the impact of the inlet air angle on temperature and airflow distribution. Additionally, this investigation will consider how the height of the warehouse influences temperature and airflow dynamics. It is essential to determine how temperature can be maintained consistently at different heights, taking into account the potential for air stratification due to density changes associated with temperature.

This study introduces a novel approach to optimizing pharmaceutical warehouse configurations for effective temperature control, an area previously unexplored in the literature. A key innovation is determining the optimal storage height for pharmaceuticals, addressing a practical industry concern. By employing a multi-objective optimization method, this research identifies the ideal process and geometric parameters to achieve uniform temperature distribution. The findings provide a scientific basis for improving pharmaceutical storage efficiency, ensuring regulatory compliance, and enhancing product integrity.

2- Problem statement

2- 1- Definition of design variables

When dealing with multiple competing objectives, multi-objective optimization[30-32] is applied to achieve a balanced solution. This method has become increasingly significant in modern industrial and economic studies. Since enhancing one objective can often compromise another, evaluating these trade-offs is essential. The goal is to determine the most effective solution that meets all objectives within permissible thresholds. In this investigation, multi-objective optimization is applied to identify the most effective quantities of certain variables to ensure that the warehouse maintains a stable and appropriate temperature. The design parameters analyzed include:

1. Height of the warehouse
2. Angle of the inlet air flow
3. Fullness of the shelves

The range of variables is presented in Table 1. The warehouse layout and shelving design were modeled after a real pharmaceutical distribution center, with dimensional variables set through expert consultations to ensure practical feasibility. In addition, Fig. 1 offers a schematic illustration of the warehouse, which clearly identifies the relevant variables. As shown in Fig. 1 there are 24 shelves in the studied warehouse. The warehouse length and the shelves width are constant.

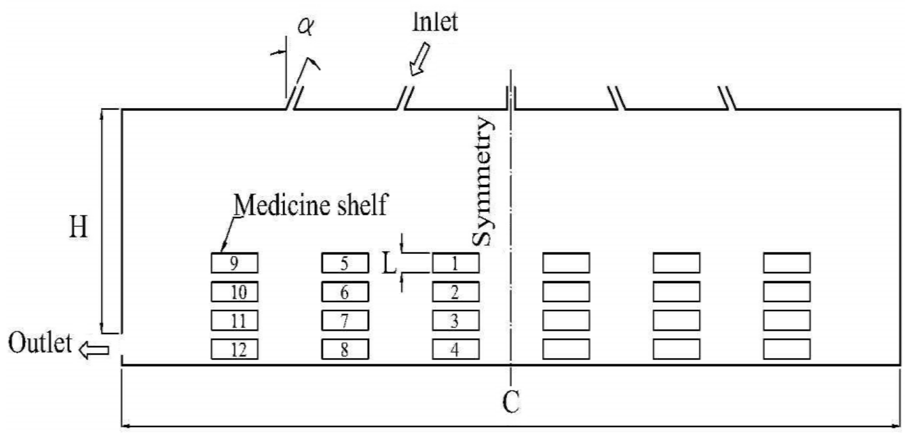

Fig. 1. Pharmaceutical warehouse and shelves, and grilles arrangement

Table 1. Design parameters range

Parameter Description	Range
H (variable part of warehouse height)	3 ~ 7 m
L (shelf height, indicative of fullness)	10 ~ 60 cm
α (Angle of the inlet air flow relative to the vertical line)	-45 ~ +45°

2- 2- Objective functions definition

To achieve an optimal temperature within the pharmaceutical warehouse, two key objectives have been identified for enhancement. The primary goal is to reduce the temperature on the shelves, while the secondary aim is to minimize the variance between the highest and lowest temperatures throughout the warehouse. This approach not only ensures that the warehouse remains sufficiently cool but also promotes uniformity in temperature distribution. It is evident that maintaining temperature uniformity can result in energy savings and improve the overall management of temperature for all pharmaceutical products.

Based on the aforementioned explanations, the problem can be formulated mathematically as follows:

$$\begin{aligned}&Minimize\ Average\ Temperature\ at\ shelves:\\&T_{ave}=f_1(H,L,\alpha)\end{aligned}$$

$$\begin{aligned}&Minimize\ \text{“}Max\ Temperature\ -\ Min\ Temperature\text{”}\\&\ at\ shelves:\Delta T=f_2(H,L,\alpha)\end{aligned}$$

$$Subjected\ to\ \begin{cases}3m<H<7m\\10cm<L<60cm\\-45°<\alpha<45°\end{cases}$$

3- Numerical modeling

3- 1- Governing equations

In this paper, the governing equations are continuity, Navier-Stokes, energy, and turbulence model equations[33]:

Continuity equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x}\left(\rho\bar{u}\right)+\frac{\partial}{\partial y}\left(\rho\bar{v}\right)=0 \tag{1}$$

Conservation of momentum equation:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\rho u_j\right)+\nabla.\left(\rho u_j\vec{V}\right)=\\&-\frac{\partial P}{\partial x_j}+\nabla.\left(\mu\nabla u_j\right)+\frac{1}{3}\frac{\partial}{\partial x_j}\left(\mu\nabla\vec{V}\right)\\&+\frac{\partial}{\partial x}\left(-\rho\overline{u'u'_j}\right)+\frac{\partial}{\partial y}\left(-\rho\overline{u'_jv'}\right)+\rho g_j\end{aligned} \tag{2}$$

Energy equation:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\rho\bar{T}\right)+\nabla.\left(\rho c_p\vec{\bar{v}}\bar{T}\right)=\\&\nabla.\left(k\nabla\bar{T}\right)+\frac{\partial}{\partial x}\left(-\rho\overline{u'T'}\right)+\frac{\partial}{\partial y}\left(-\rho\overline{v'T'}\right)+S_T\end{aligned} \tag{3}$$

Turbulence model equations:

$$\begin{aligned}&\frac{\partial}{\partial x}\left(\rho uk-\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right)\\&+\frac{\partial}{\partial y}\left(\rho vk-\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right)=G-\rho\varepsilon\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial}{\partial x}\left(\rho u\varepsilon-\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x}\right)\\&+\frac{\partial}{\partial y}\left(\rho v\varepsilon-\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial y}\right)\\&=\frac{\varepsilon}{k}\left(c_1G-c_2\rho\varepsilon\right)\end{aligned} \tag{5}$$

Where G is defined as:

$$G=\mu_t\left[2\left(\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right)+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right] \tag{6}$$

Table 2. Boundary Conditions and Other Constant Parameters

Parameter Description	Range
Inlet air velocity	3 m/s
Inlet air temperature	18 °C
Walls temperature	47 °C
Warehouse length	30 m
Shelf width (accessible from both sides)	1.8 m

3- 2- Boundary conditions

For the purpose of simulation, it is essential to establish boundary conditions for the equations previously mentioned. The inlet air velocity and temperature are predetermined. The wall temperatures are treated as constant, and it is assumed that the shelves, once thermal equilibrium is achieved, exhibit no heat transfer, functioning as insulated surfaces. A symmetry boundary condition has been implemented at the symmetry axis. The boundary conditions outlined above, along with other constant parameters relevant to this study, are detailed in Table 2. The selected range covers a wide spectrum, such as airflow nozzle angles from -45° to +45°, exceeding the typical commercial limit of ±30°. A wall temperature of 47°C was chosen to simulate extreme summer conditions in Iran, assessing system performance under worst-case scenarios. Ministry of Health regulations mandate a storage temperature of 15–25°C, extendable to 30°C under certain conditions, making this evaluation crucial for compliance and efficiency.

To numerically solve the flow field, the finite volume method is employed. The discretization of the momentum and energy equations is performed using second-order upwind schemes, while the pressure is discretized using a standard approach. The coupling of pressure and velocity is carried out using the SIMPLE algorithm. A pressure under-relaxation factor of 0.3 is used, along with under-relaxation factors for density, body force, and energy set to 1, and an under-relaxation factor for momentum set to 0.7. To ensure the independence of the results from the mesh size, four meshes with different sizes were considered, and the difference between maximum and minimum temperature (were examined with the number of cells. The results from this investigation are shown in Fig. 2.

It can be observed that as the mesh becomes finer, the temperature difference decreases. The mesh with 243,000 cells has a relative difference of 2.5% compared to the finest grid. This mesh was selected for further studies, and a representation of it is shown in Fig. 2. Illustrated in Fig. 2 is the mesh developed for the geometry being studied, which includes 243,000 elements. With the orderly arrangement of this mesh, it is projected that the problem will be solved with a level of accuracy deemed acceptable.

To validate the heat transfer coefficient inside a channel with a constant temperature on its walls, the Dittus-Boelter equation for turbulent flow[34] was compared using the modeling presented for the case where air flows inside the channel. The results are displayed in Fig. 3. The relative difference between the results of the two studies shows an error range of 3-15 percent.

4- Results

4- 1- Parametric study

In this section, a parametric study is carried out concerning the three variables listed in Table 1, namely the height of the warehouse, the angle of the inlet air flow, and the fullness of the shelves. The effects of warehouse height on key variables are demonstrated in Fig.s 4 and 5. Fig. 4 demonstrates that as the height of the warehouse increases, both the average temperature of the shelves and the difference between maximum and minimum temperatures decrease. This relationship implies that greater height within the specified range is associated with improved temperature conditions. Additionally, Fig. 5 presents the temperature and velocity contours corresponding to various warehouse heights. The unsuitability of low-height warehouses for attaining desirable temperatures is primarily due to the short distance from the inlet grille to the shelves, which restricts the airflow and impairs the heat exchange process with the shelves. As the height increases from 3 to 5 and 7 m, the average temperature decreases by 1.4% and 2.2%, respectively, and the temperature difference decreases by approximately 32% and 42.2%. As the height of the storage increases, the average velocity in the warehouse decreases. With the decrease in average velocity, convective heat transfer also diminishes. This increase in convective thermal resistance weakens heat transfer and results in a greater temperature difference within the warehouse environment (see Fig. 5).

The effects of shelf fullness on objective variables are depicted in Fig.s 6 and 7. Fig. 6 demonstrates that the mean temperature and the differential between maximum and minimum temperatures are at their highest when the shelves are semi-full, which is not desirable from a thermal point of view. The contour analysis in Fig. 7 identifies the upper shelf near the left wall as the most unfavorable location. It appears that nearly empty shelves allow for larger air pathways, which enhances heat transfer between the shelves and the air, resulting in a more desirable temperature. In contrast, the contours indicate that shelves that are almost full create

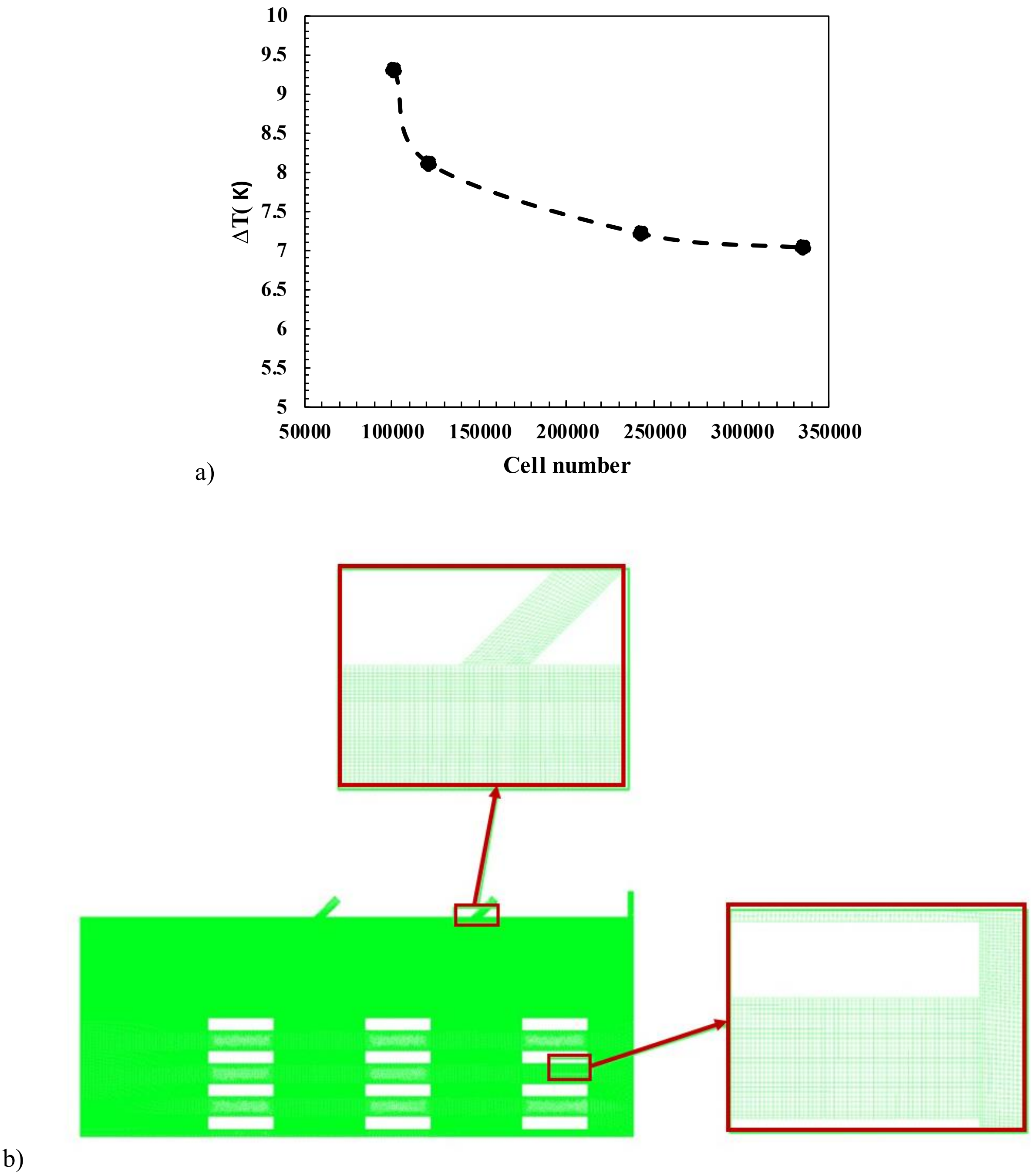

Fig. 2. a)grid study and b) a view of the chosen grid

smaller air pathways; These forces more airflow over the upper shelf of the left column, leading to a more favorable temperature in the critical shelf (number 9) compared to the semi-full condition.

Fig.s 8 and 9 illustrate the influence of the inlet air flow angle on the objective variables. In contrast to the two other parameters, the impact of the air inlet angle on the two objective variables - average temperature and temperature difference - exhibits opposing trends, as indicated by the varying concavities in Figure 8. The velocity contour presented in Fig. 9 shows that at an angle of 0 degrees, the flow distribution is more uniform, resulting in a decrease in average temperature; however, the difference between the maximum and minimum temperatures is greater than that observed at angles of ±45 degrees.

Fig. 10 illustrates the variations in temperature across shelves, both horizontally and vertically. The graphs representing shelves 1 through 12 are differentiated by distinct colors. The X-direction graph indicates that shelves 1 to 4 maintain lower temperature levels. Aside from shelf number 4, which is notably different from the others, the temperatures of shelves 1 through 3, including their upper

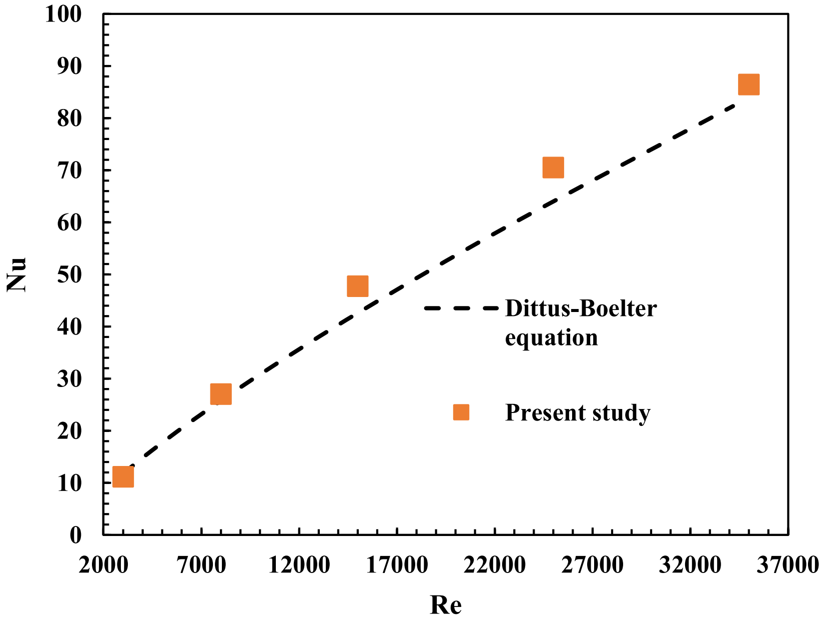

Fig. 3. The validation of results with Ref.[34]

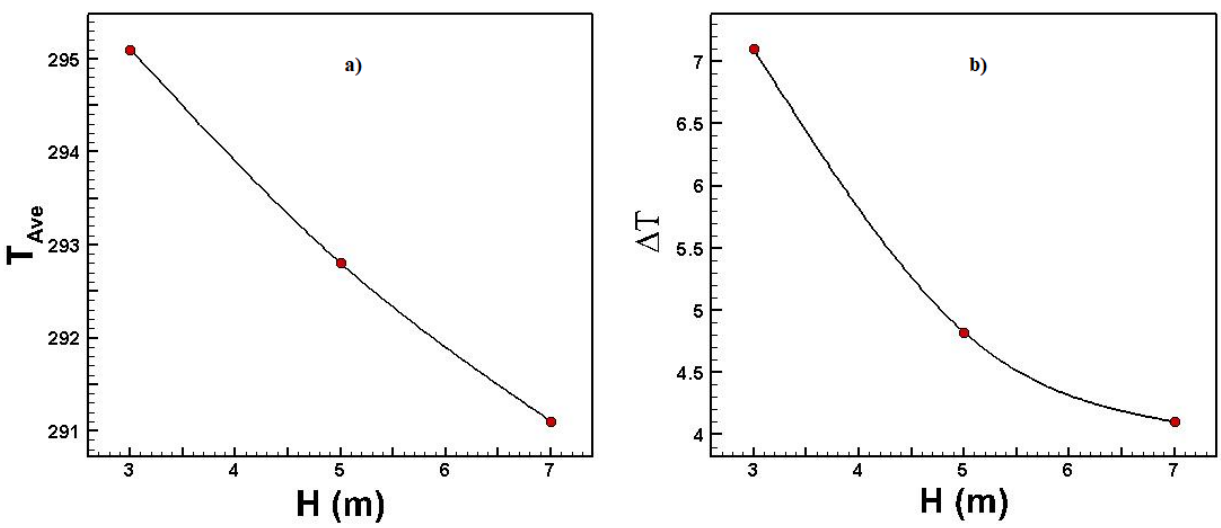

Fig. 4. Variations of a)mean temperature(T_{Ave}) and b)difference between maximum and minimum temperature(ΔT) values (K) for different heights of the warehouse

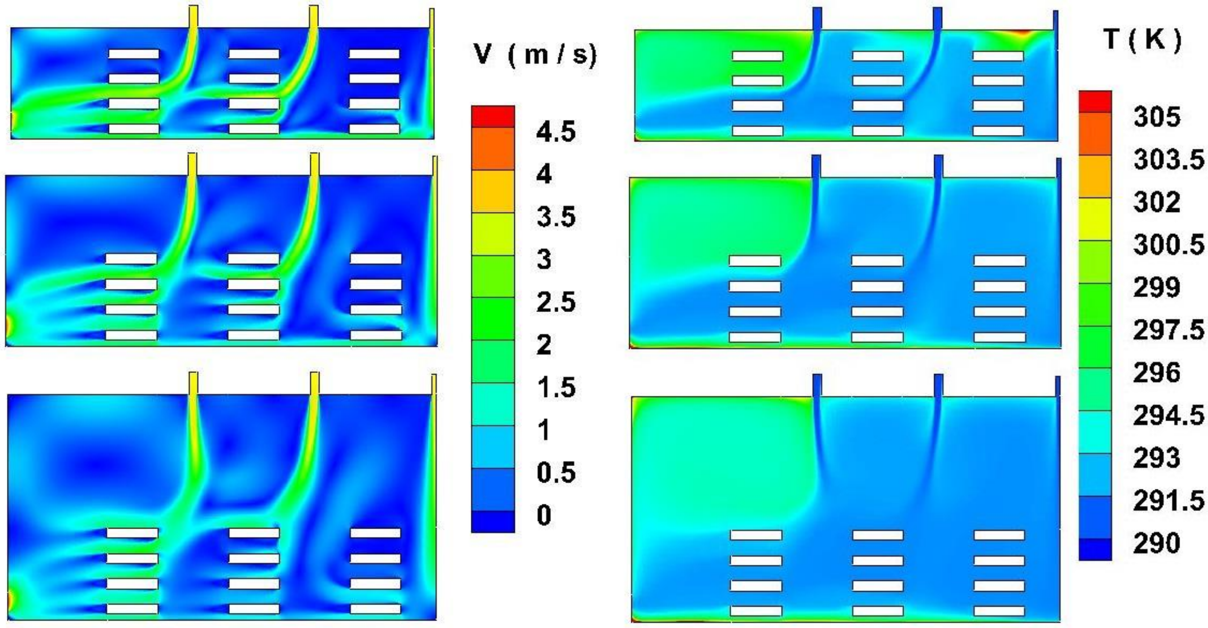

Fig. 5. Air velocity and temperature contours for different heights of the warehouse

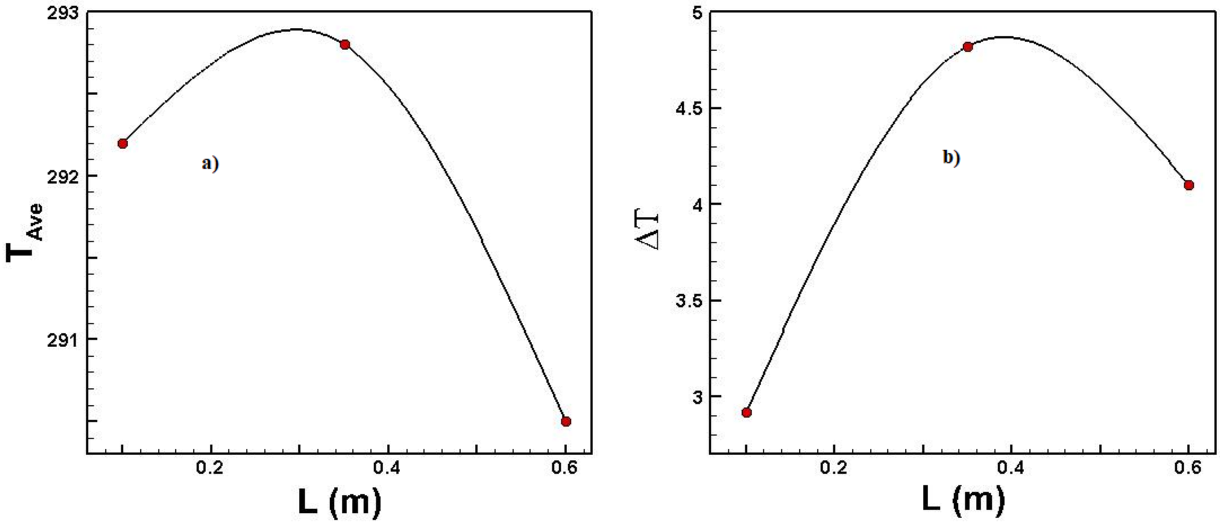

Fig. 6. Variations of a)mean temperature(T_{Ave}) and b)difference between maximum and minimum temperature(ΔT) values (K) for different values of shelf fullness

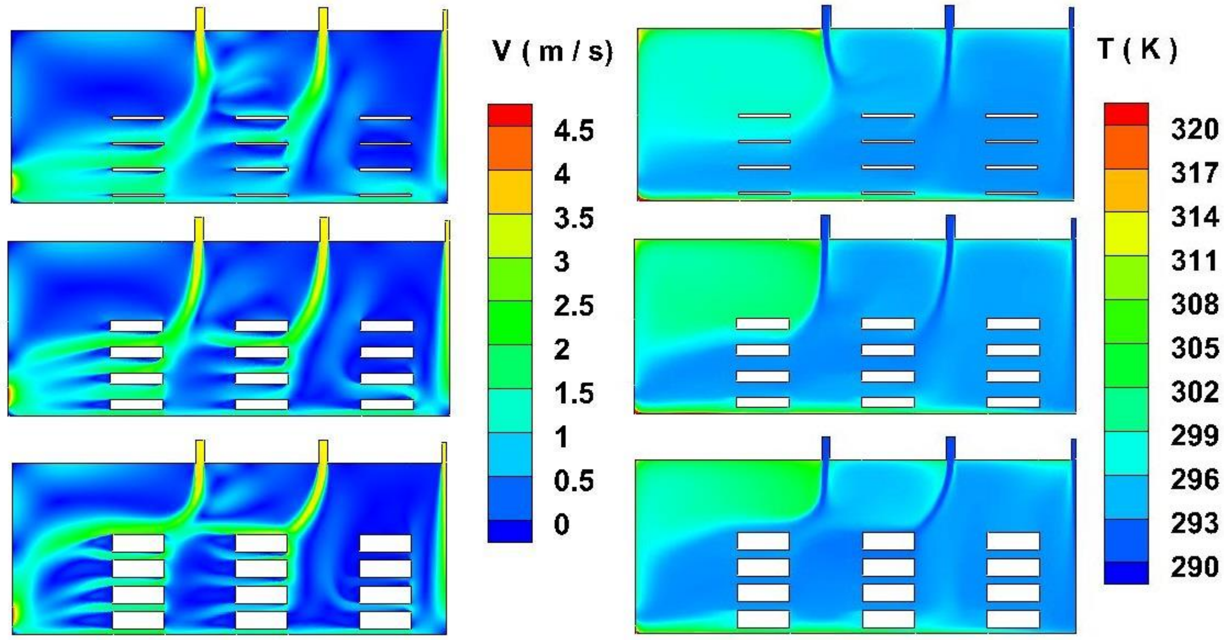

Fig. 7. Air velocity and temperature contours for different values of shelf fullness

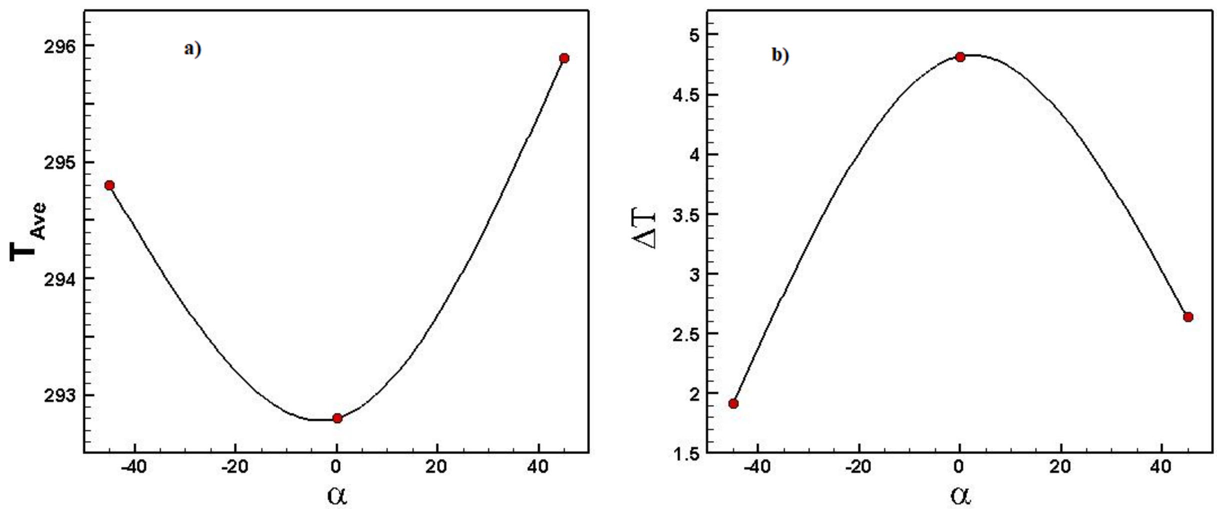

Fig. 8. Variations of a) mean temperature (T_{Ave}) and b)difference between maximum and minimum temperature(ΔT) values (K) for different inlet air angles

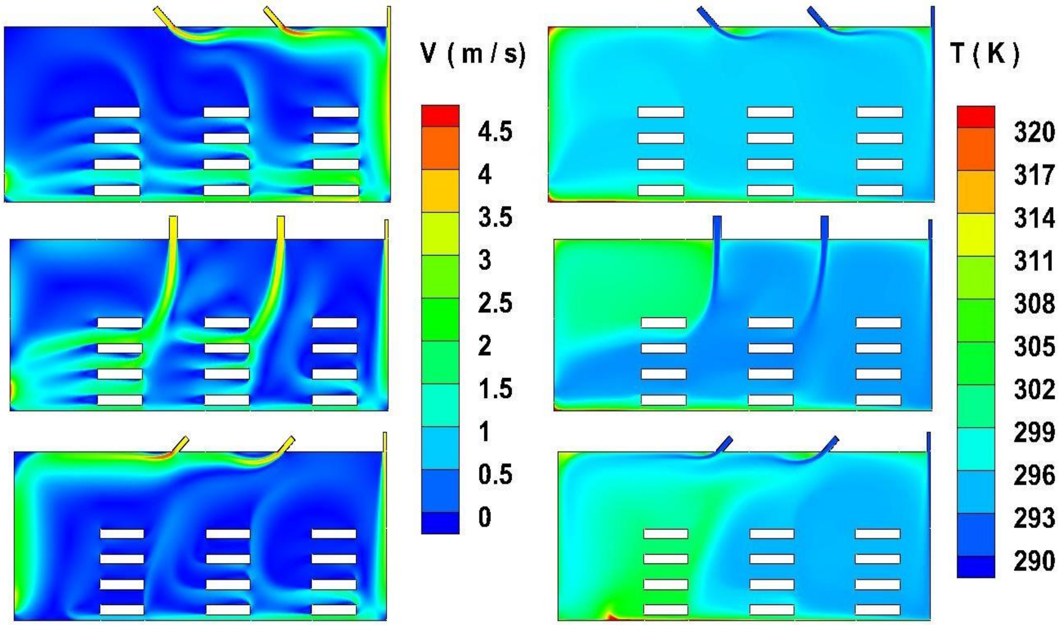

Fig. 9. Air velocity and temperature contours for different inlet air angles

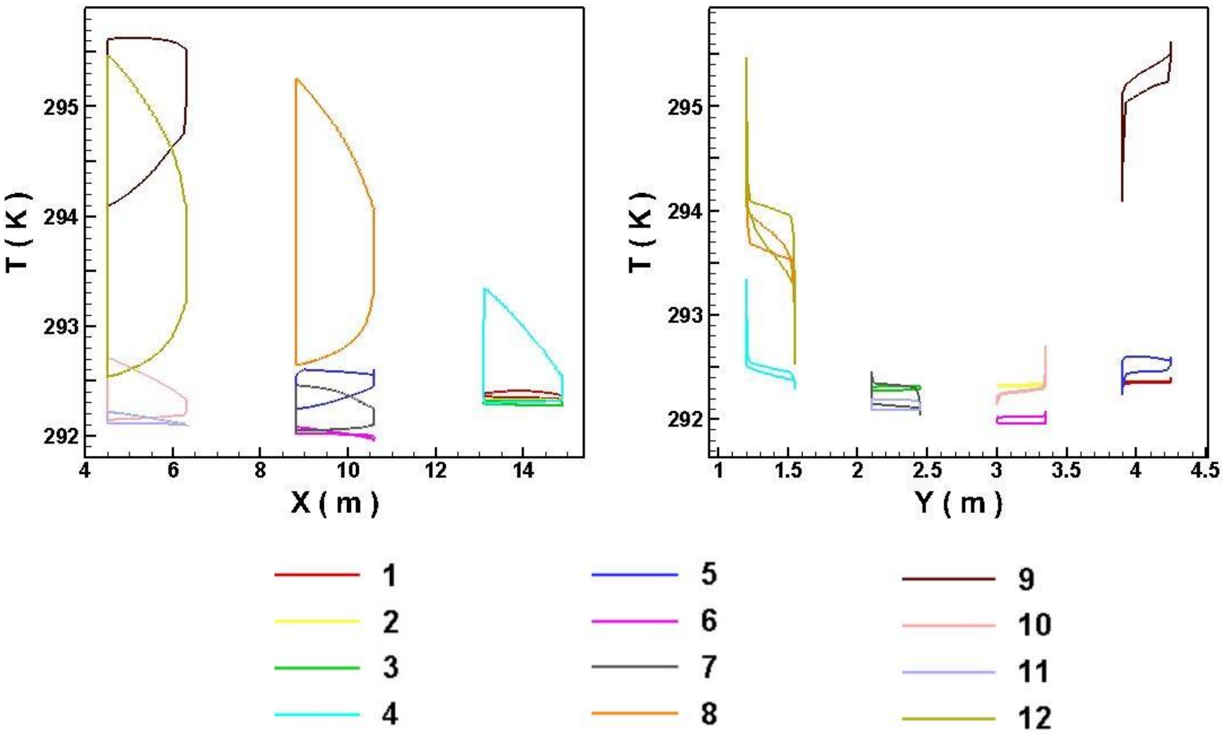

Fig. 10. Variations of the temperature on horizontal and vertical surfaces of shelves

and lower surfaces, are approximately uniform at around 19.5 °C. These shelves are located in the middle of the warehouse and are situated at the largest distance from the side walls, making these temperature levels predictable. As the shelves are located further from the warehouse's center, both the overall temperature and the temperature differential between the upper and lower surfaces tend to rise.

Within the shelf columns "1 to 4" and "5 to 8," the highest temperatures are found on the lower shelves, which are positioned closest to the floor. In contrast, the column "9 to 12" indicates that the lowest shelf has the second highest temperature, just below that of the upper shelf. This minor temperature difference in this column, relative to the others, is primarily due to the effects of the side wall and the outlet grille. The short distance between the grille and the lowest shelf (number 12), along with the air suction in that vicinity, results in this shelf being ranked as the second warmest.

The graph representing the Y-direction indicates that the middle rows (second and third) have lower temperatures characterized by greater uniformity, while the upper and lower rows show higher average temperatures with less uniformity. In the lower row, temperatures decline as the Y value increases, which aligns with the expectation that the distance from the warm floor is increasing. However, in the second and third rows, the impact of increasing Y on temperature is negligible, as external factors like walls exert little influence, and the airflow across these two row surfaces appears to be similar. In the upper row, shelf number 9, which is situated closer to the side wall, displays a significant temperature range, with temperatures increasing as Y rises. Shelves 1 and 5 exhibit temperature behaviors that are comparable to those of the middle rows.

4- 2- Optimization

In this research, in addition to a parametric study, multi-objective optimization has been performed to identify the optimal values of parameters that yield the desired temperature and temperature range as illustrated in Fig. 11. Based on ANSYS Fluent's recommendation, the Adaptive Multi-Objective Optimization (AMO) method[35] has been applied to enhance the optimization process. This approach dynamically refines the search for optimal solutions while simultaneously addressing multiple conflicting objectives, ensuring an efficient and balanced exploration of the design space. The number of initial samples is 26, the number of design points is 46, and the number of candidates is 3(Table 3). Finally, the optimal point is selected after analysis. While the average temperature of all three candidates is close, the selected point was chosen due to its slightly better temperature performance. Additionally, the other two points were found to have suboptimal shelf occupancy, with only 12 cm filled, whereas the selected point had a relatively better occupancy of 18 cm.

Table 3 presents the values of the parameters at the optimal point. Variable part of the warehouse height is 6.16 m in the optimal point, which is close to the upper limit considering the range of 3 to 7 m. This fact confirms Fig. 3 contents in the parametric study section. Low height for the warehouse is not suitable for temperature setting because the short distance from the inlet grille to the shelves restricts the airflow and impairs the heat exchange process with the shelves.

An optimal shelf height of 18 cm, indicative of shelf fullness, is anticipated due to the limited volume of medicine, which facilitates adequate airflow and contributes to achieving a more favorable temperature. An inlet air angle

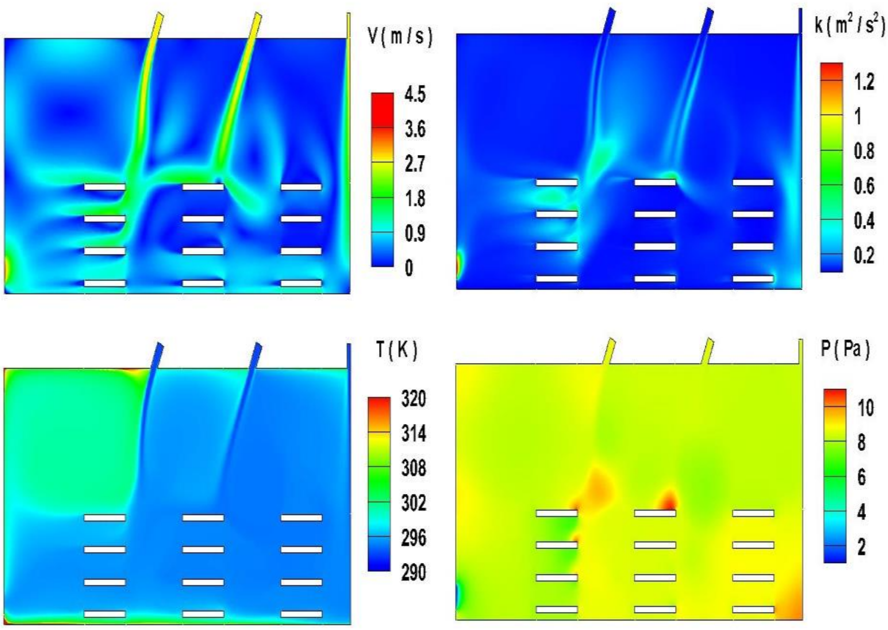

Fig. 11. Turbulent kinetic energy and air velocity, pressure, and temperature contours in the optimal point

Table 3. Parameters Value at Candidate Points

	Candidate Point		
No.	1	2	3
H (m)	6.162	5.600	5.543
L (m)	0.186	0.127	0.127
α (degree)	113.397	85.652	82.444
T_{ave} (K)	292.322	292.696	292.875
$\Delta T(K)$	0.56189	0.335815	0.556366

Table 4. Parameters Value at Optimal Point

Parameter Description	Range
H (variable part of warehouse height)	6.16 meters
L (shelf height, indicative of fullness)	18 cm
α (Angle of the inlet air flow relative to the vertical line)	23°

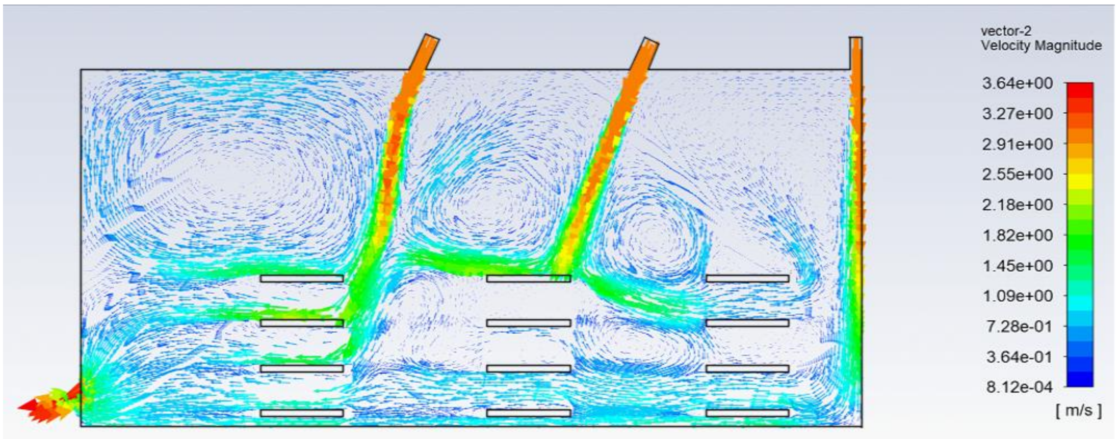

Fig. 12. Velocity vectors in the optimal point

of 23° facilitates optimal air circulation among the shelves, taking into account the positioning of the outlet grille. A positive angle is anticipated because negative angles could disrupt airflow on both sides of the symmetry axis and interfere with the central vertical airflow, which is maintained at 0°, thereby leading to increased energy losses. The velocity vector at the optimal point is illustrated in Fig. 12, which can assist in clarifying the explanation provided earlier.

5- Conclusion

This study presents a comprehensive parametric analysis and multi-objective optimization of the flow and temperature distribution in pharmaceutical warehouses, focusing on the effects of fresh air inlet angle, warehouse height, and shelves fullness. Utilizing two-dimensional simulations conducted with ANSYS-Fluent, we have demonstrated that increasing the height of the warehouse within the specified range contributes to achieving a more acceptable and uniform temperature distribution. A summary of the findings of the present study is provided below:

Our findings indicate that the configuration of shelves plays a critical role in temperature management; specifically, a medium level of shelf occupancy leads to the worst temperature conditions, considering both the average quantity and uniformity. Altogether, shelves that hold a relatively low amount of medicines yield the most favorable temperature environment.

Additionally, we observed that an increase in the fresh air inlet angle relative to the vertical line results in undesirable temperature rises and reduced uniformity. In terms of horizontal temperature distribution, shelves positioned further from the symmetry axis exhibit higher temperatures and less uniformity, while vertically, middle shelves outperform both upper and lower shelves in terms of temperature consistency.

The optimization results highlight an optimal configuration that balances both temperature and its uniformity, providing valuable insights for warehouse design in the pharmaceutical industry.

This research underscores the importance of strategic design choices in enhancing temperature control and ensuring product integrity within pharmaceutical storage environments. Future work may explore additional variables and real-world applications to further refine these findings.

Nomenclature

A	Area, m^2
u,v,w	Velocity, m/s
P	Pressure, kPa
T	Temperature,K
K	Thermal conductivity coefficient,W/mK
g	Gravity acceleration, m/s^2
H	variable part of warehouse height, m
L	shelf height, indicative of fullness,m

Greek symbols

ρ	Density, kg/m^3
μ	Viscosity,Pa.s
α	Angle of the inlet air flow relative to the vertical line, °
ε	Turbulent dissipation rate, m^2/s^3
k	Turbulent kinetic energy, m^2/s^2

Subscript

f	Fluid
T	Turbulence

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